Simulation Center for Runaway Electron Avoidance and Mitigation

a new US collaborative center

Dylan Brennan
Plasma Physics Laboratory
Princeton University

Presented at the TSDW Workshop
July 21, 2016

SCREAM is a Collaboration between FES and ASCR Researchers

Team Includes 9 Institutions with 12 PI's
8 Associated with FES
4 Associated with ASCR

Principal Investigators:

- FES:
  - Dylan Brennan (Princeton University)
  - Xianzhu Tang (Los Alamos National Laboratory)
  - Amitava Bhattacharjee (Princeton Plasma Physics Laboratory)
  - Allen Boozer (Columbia University)
  - Boris Breizman (University of Texas, Austin)
  - Diego Del-Castillo-Negrete (Oak Ridge National Laboratory)
  - Valerie Izzo (University of California, San Diego)
  - Lang Lao (General Atomics)
- ASCR
  - Mark Adams (Lawrence Berkeley National Laboratory)
  - Luis Chacon (Los Alamos National Laboratory)
  - Irene Gamba (University of Texas, Austin)
  - Gunnan Zhang (Oak Ridge National Laboratory)

Team will combine theoretical models with advanced simulation and analysis facilitated by direct participation of ASCR SciDAC institutes to focus on the runaway risk for ITER and tokamaks in general.

Outline

- Clear Need for US Center on Runaway Electron Theory and Simulation
  - Results of Recent Workshops Pointed to the Need
  - Recent Advances Setting the Stage
- Important issues remain to be predictive
  - Interaction with magnetic fluctuations a key need
  - Advanced Computing necessary component
- The SCREAM Collaboration
  - Who, Where and What
  - Goals and Scope
  - Continuum, Monte Carlo and Probability methods each contribute
- Concluding Remarks

Outline

- Clear Need for US Center on Runaway Electron Theory and Simulation
  - Results of Recent Workshops Pointed to the Need
  - Recent Advances Setting the Stage
- Important issues remain to be predictive
  - Interaction with magnetic fluctuations a key need
  - Advanced Computing necessary component
- The SCREAM Collaboration
  - Who, Where and What
  - Goals and Scope
  - Continuum, Monte Carlo and Probability methods each contribute
- Concluding Remarks

Recent Workshops and Exascale Review Highlighted Need for a Center

- Need for progress in runaway electron physics was clearly made in both the 2015 Integrated Simulations and Transients workshops, and simulation of disruptions has been a recent focus of the 2016 Exascale Requirements Review, all three involving partnerships between FES and ASCR.
  - C. Greenfield and R. Nazikian. Report on scientific challenges and research opportunities in transient research, 2015.
  - P. Bonoli and L.C. McInnes. Report of the workshop on integrated simulations for magnetic fusion energy sciences, 2015.

- An eventual reliable design tool for runaway mitigation requires almost the full functionality of the whole device modeling (WDM) of a tokamak, the proposed physics studies will naturally lead to a runaway physics module for WDM.

Recent progress has accelerated - quantitative understanding of experiments advancing

Multiple groups have accelerated effort in the last two years (2015 papers)

- IFS, IPP and ITER: Monte Carlo methods and rigorous marginal E analytics
  - P. Aleynikov, B. Breizman, Phys. Rev. Lett., **114**, 155001 (2015)
- Columbia: Theoretical analyses of runaway dynamics
  - A. Boozer, Phys. Plasmas **22**, 032504 (2015)
- PPPL: Adjoint Fokker-Planck runaway probability solutions and Monte Carlo simulations
  - C. Liu, D.P. Brennan, A. Bhattacharjee, and A.H. Boozer, Phys. Plasmas 23, 010702 (2016).
- GA: MHD Simulations and tracer particles
  - V.A. Izzo, D.A. Humphreys, and M. Kornbluth, Plasma Phys. Control. Fusion 54, 095002 (2012).
- ORNL: Impurity transport and interactions with RE, thermal anisotropy, Monte Carlo
  - D. del-Castillo-Negrete, L. Carbajal, L. Baylor, D. Spong, S. Seal
- LANL: Phase space structure and runaway transport processes
  - Z.Guo, C. Mcdevitt and X. Tang, Proceedings of the International Sherwood Fusion Theory Confernece, Madison, Wisconsin, April 2016.
- Chalmers Group: continuum solver for RE distributions and time dependent simulations
  - Stahl, Hirvijoki, Decker, Embréus and Fülöp, PRL **114**, 115002 (2015)
  - Hirvijoki, Pusztai, Decker, Embréus, Stahl and Fülöp, JPP (2015)

Improvements to the kinetic model have been made across the community

- Improved operators used for secondary generation
  - Take into account the seed RE momentum and pitch angle distribution
  - Secondary RE momentum constrained
  - Energy and momentum conservation
- Detailed forces in the kinetic equation
  - Synchrotron radiation
  - Cerenkov radiation
  - Bremsstrahlung radiation
- Trapping effects included in some studies
  - Radial dependence of trapping (not shown here)

$$\frac{\partial f}{\partial t} + E\{f\} + C\{f\} + R\{f\} = S$$

E: Electric field drive
C: Collision operator
R: Synchrotron radiation back-reaction force
S: Secondary runaway electron generation

Outline

- Clear Need for US Center on Runaway Electron Theory and Simulation
  - Results of Recent Workshops Pointed to the Need
  - Recent Advances Setting the Stage
- Important issues remain to be predictive
  - Interaction with magnetic fluctuations a key need
  - Advanced Computing necessary component
- The SCREAM Collaboration
  - Who, Where and What
  - Goals and Scope
  - Continuum, Monte Carlo and Probability methods each contribute
- Concluding Remarks

Important issues with RE dynamics remain to be addressed to be predictive about the DMS

- RE interaction with High-Z impurities
- Seed distribution (hot tail) effects in thermal quench events
- Spatial / configuration space dependence
- Kinetic instability
  - Whistler wave scattering
  - Bump on tail?
- Magnetic fluctuation
- MHD instability coupling
- RE termination (magnetic energy conversion), RE-wall interaction

Collaborative center needed to address best technical methods for coupling the runaway electron, impurity transport, and MHD simulation codes, managing and visualizing the large volumes of data, and determining its uncertainty, both in experiment and in simulation.

Collaboration needed between theory, simulation and algorithmic development

Center will assemble experts in runaway electron physics, tokamak disruptions, magnetohydrodynamics (MHD) simulations, and advanced computing.

Theory: Analytic plasma theory, or employing light weight code for analysis

Simulation: Production code development/improvement and large simulations

Algorithms: Designing, implementing and testing innovative algorithms and performance enhancements for runaways

Open questions remain as to the best technical methods for coupling the runaway electron, impurity transport, and MHD simulation codes, managing and visualizing the large volumes of data, and determining its uncertainty, both in experiment and in simulation.

Needed to address physics questions

Outline

- Clear Need for US Center on Runaway Electron Theory and Simulation
  - Results of Recent Workshops Pointed to the Need
  - Recent Advances Setting the Stage
- Important issues remain to be predictive
  - Interaction with magnetic fluctuations a key need
  - Advanced Computing necessary component
- The SCREAM Collaboration
  - Who, Where and What
  - Goals and Scope
  - Continuum, Monte Carlo and Probability methods each contribute
- Concluding Remarks

SCREAM is a Collaboration between FES and ASCR Researchers

Team Includes 9 Institutions with 12 PI's
8 Associated with FES
4 Associated with ASCR

Principal Investigators:

- FES:
  - Dylan Brennan (Princeton University)
  - Xianzhu Tang (Los Alamos National Laboratory)
  - Amitava Bhattacharjee (Princeton Plasma Physics Laboratory)
  - Allen Boozer (Columbia University)
  - Boris Breizman (University of Texas, Austin)
  - Diego Del-Castillo-Negrete (Oak Ridge National Laboratory)
  - Valerie Izzo (University of California, San Diego)
  - Lang Lao (General Atomics)
- ASCR
  - Mark Adams (Lawrence Berkeley National Laboratory)
  - Luis Chacon (Los Alamos National Laboratory)
  - Irene Gamba (University of Texas, Austin)
  - Gunnan Zhang (Oak Ridge National Laboratory)

Team will combine theoretical models with advanced simulation and analysis facilitated by direct participation of ASCR SciDAC institutes to focus on the runaway risk for ITER and tokamaks in general.

Collaboration aims to advance understanding and quantitative prediction of runaway physics

Overall Goals

- Establish the physical basis for generation and evolution
- Explore scenarios for avoidance
- Investigate the leading candidates for mitigation

Initial Scope

- Theoretical investigation of runaway physics and mitigation
- Scoping studies of runaway electron generation with reduced modeling.
- Relativistic Vlasov-Fokker-Planck simulations of runaway electrons using phase-space discretization.
- Modeling of Disruptions and Runaway Electrons with NIMROD
- Simulating of Runaway Seed Current Generation with XGC1
- Monte Carlo simulations of runaway electrons with KORC

Computational Methods

- Relativistic Fokker-Planck solvers using grid discretization in phase space
- Self-consistent particle-in-cell
- Particle-based Monte-Carlo
- MHD-particle hybrid

Cross-check between these different methods will provide an additional means for verification and will further bolster the fidelity of physics predictions.

Kickoff meeting Friday after TSDW

SCREAM Team Meeting Agenda
Princeton Plasma Physics Laboratory - B318
Princeton, New Jersey
July 22, 2016
1:00PM-5:15PM

Introduction:
1:00-1:05 Dylan Brennan: Welcome and introductory remarks
1:05-1:10 John Mandrekas: Remarks on SCREAM within the FES program
1:10-1:15 Randall Laviolette: Remarks on SCREAM within the ASCR program

Technical Talks:
1:15-1:40 Allen Boozer: Runaway avoidance and mitigation on ITER (25)
1:40-2:00 Xianzhu Tang: LANL Physics Plan (20)
2:00-2:20 Luis Chacon: LANL computational math plan (20)
2:20-2:45 Val Izzo: Status and Plans for Runaway Electron Capabilities in NIMROD (25)
2:45-3:00 Dylan Brennan : Nonlinear collisional generation of runaway electron seed distributions (15)
3:00-3:20 Coffee Break
3:20-3:45 Eero Hirvijoki : A density-, momentum-, and energy-conserving finite-element method for the Landau collision operator (25)
3:45-4:10 Mark Adams : Solver, Mesh, and Discretization, and Particle-in-cell, Support in PETSc (25)
4:10-4:35 Irene Gamba : Galerkin methods applied to collisional transport in flows along manifolds generated by coordinates depending on Lorentztian forces (25)
4:35-4:50 Gunnan Zhang: Stochastic method to simulate the runaway probabilities of electrons and UQ methods to study parameter dependence. (15)
4:50-5:15 Leopoldo Carbajal : Status and future developments on KORC (25)

Adjourn

Team Dinner:
6:30-8:30PM Location TBD

Outline

- Clear Need for US Center on Runaway Electron Theory and Simulation
  - Results of Recent Workshops Pointed to the Need
  - Recent Advances Setting the Stage
- Important issues remain to be predictive
  - Interaction with magnetic fluctuations a key need
  - Advanced Computing necessary component
- The SCREAM Collaboration
  - Who, Where and What
  - Goals and Scope
  - Continuum, Monte Carlo and Probability methods each contribute
- Concluding Remarks

Concluding Remarks

This is a new beginning!

SCREAM will serve as a US counterpart to the CEA efforts (Y. Peysson) and directly contribute to ITPA.

Continuing Progress : Multiple groups now in quantitative consensus on several radiative effects on runaway dynamics. Much progress in fundamental theory over past few years.

Advanced Computing Needed : Theory community addressing physics and validation against experiment, but open questions remain, some best addressed through development in advanced computing.

SCREAM will help community address questions accessible through combining theory developments with advanced computing, such as interaction with magnetic fluctuations, to be quantitatively predictive on avoidance and mitigation.